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Performance Evaluation of Mobile WiMAX with MIMO and Relay Extensions

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***Abstract*-The latest mobile WiMAX standard promises to deliver high data rates over extensive areas and to large user densities. More specifically, data rates are expected to exceed those of conventional cellular technologies. The IEEE 802.16e WiMAX standard enables the deployment of metropolitan area networks to mobile terminals in non-line-of-sight radio environments. Current concerns include leveraging high data rates, increasing area coverage, and competing with beyond 3G networks. Based on the IEEE 802.16e wirelessMAN-OFDMA (Orthogonal Frequency Division Multiple Access) physical (PHY) layer air-interface, this paper presents a physical layer study of MIMO enabled mobile WiMAX in an urban environment. The radio channels are based on those developed in the European Union IST-WINNER project. Results are given in terms of system throughput and outage probability with and without relays for a range of SISO, MISO and MIMO architectures. Results show that satisfactory performance cannot be achieved in macrocells unless radio relays are used in combination with MIMO-STBC.**

***Keywords*-IEEE802.16e, WiMAX, MIMO, diversity, link adaptation, relays**

I. INTRODUCTION

WiMAX (Worldwide Interoperability for Microwave Access) is central to a number of new market and technology opportunities. The standard offers a range of broadband wireless technologies that are capable of delivering differentiated and optimized service models. WiMAX promises to combine high capacity services with wide area coverage. However, issues such as power and spectral efficiency still need to be resolved. In 2004, the IEEE 802.16d standard [1] was published for Fixed Wireless Access (FWA) applications. In December 2005 the IEEE ratified the 802.16e [2] amendment, which aimed to support Mobile Wireless Access (MWA) with seamless network coverage. This standard is now receiving considerable industrial attention.

The mobile WiMAX air interface adopts Scalable Orthogonal Frequency Division Multiple Access (SOFDMA) for improved multipath performance in non-line-of-sight (NLoS) environments. SOFDMA provides additional resource allocation flexibility. 802.16e transmits using a group of subchannels (the number of which can be varied), and these can be adaptively optimized to maximize performance. Spectrum resources can be adapted to densely or sparsely populated regions, making it suitable for urban or rural FWA and MWA. The WiMAX forum has proposed a number of profiles; these cover 5, 7, 8.75 and 10MHz channel bandwidths for operation in worldwide licensed bands at 2.3, 2.5, 3.3 and 3.5GHz [3].

In a practical urban environment, the radio channel linking the BS to the MS is unpredictable and depends on the specific application scenario. However, for mobile applications LoS is rarely achieved. Multiple-Input Multiple-Output (MIMO) systems have the ability to exploit NLoS channels, and hence increase spectral efficiency compared to a Single-Input Single-Output (SISO) system. MIMO advantages include diversity gains, multiplexing gains, interference suppression, and array gains. Mobile WiMAX supports a full range of smart antenna technologies, including Space Time Block Codes (STBC), Spatial Multiplexing (SM), and beamforming. MIMO is seen as a critical component in future developments of mobile WiMAX. Suitable MIMO orientated link adaptation strategies are critical to exploit the wide of range of MIMO systems and channel conditions [4]. For example, STBC offers diversity gain, but cannot improve capacity without the use of Adaptive Modulation and Coding (AMC). SM combined with higher order modulation schemes can increase the peak throughput, but such schemes require extremely high SNR levels [4]. In practical urban cells it will be difficult to exploit SM at the cell edge. The inclusion of MIMO techniques alongside flexible sub-channelization and AMC enables Mobile WiMAX technology to improve system coverage and capacity. Importantly, if correctly configured, these benefits will be achieved using power and spectrum efficient terminals.

The implementation and application of MIMO in a mobile WiMAX application requires further research to achieve an efficient and cost-effective solution. Furthermore, coverage is still a key issue for mobile WiMAX users, with desired operating ranges of 1.5 km per cell. It is well-known that radio relays can be deployed to enhance coverage (and in some cases capacity) [5][6].

This paper focuses on the above challenges, and includes a comprehensive study of MIMO enabled mobile WiMAX with and without the use of radio relays. The paper provides a numerical analysis of the capacity and coverage expected for urban deployments. The work places specific emphasis on the downlink (DL). The limitations of WiMAX without the use of MIMO are first identified, and the advantages of STBC and SM in combination with OFDMA are then evaluated. The use of AMC (switching from QPSK to 64-QAM) is considered to maximize the throughput of each individual link. Results are shown in terms of throughput, coverage and spectral efficiency for urban microcells and macrocells, as defined by 3GPP2 [7]. The channel models developed within the European Union IST-WINNER [8] project are used. A general relay concept and deployment is also presented for coverage and capacity enhancement at the cell edges.

The remainder of this paper is organized as follows. Section II briefly describes the mobile WiMAX system profile. Section III presents performance results using the WINNER channel models for urban microcell and macrocell environments. Throughput, coverage and spectrum efficiency results are presented and analyzed in section IV. Finally, the paper ends with a set of conclusions.

II. MIMO WiMAX: System Description

The mobile WiMAX system makes use of the wireless-MAN-OFDMA air interface. In essence, the principle of OFDMA consists of different users sharing the Fast Fourier Transform (FFT) space. The architecture is based on a scalable sub-channelization structure with variable FFT sizes according to the channel bandwidth. With flexible channelization, each user may be assigned one or more sub-channels, and several users may transmit simultaneously in each time-slot. Initial profiles under development in the WiMAX Forum Technical Working Group for release-1 specify bandwidths of 5 and 10MHz, with an FFT size of 512 and 1024 [3].

The great advantage of OFDMA is its tolerance to multipath propagation and frequency selective fading in a mobile environment. The use of a Cyclic Prefix (CP) can completely eliminate Inter Symbol Interference (ISI) so long as its duration is longer than the maximum channel delay spread. Table 1 lists the FFT parameters for a 512-FFT OFDMA system using 5MHz of bandwidth. The use of a CP equal to 1/8th of the OFDMA symbol period ensures that up to 11.2µs of delay spread can be tolerated. This introduces an overhead of approximately 10% [9].

TABLE 1
FFT PARAMETERES IN A 5 MHZ BANDWIDTH

Parameters	Values
Bandwidth	5 MHz
FFT size (N_{FFT})	512
Useful symbol time (T_b)	89.6 µs
Guard time (T_g)	11.2 µs
OFDMA symbol time (T_s)	100.8 µs
Subcarrier frequency spacing (Δf)	11.16071429 kHz
Sampling frequency (F_{samp})	5.714 MHz
Sampling time (T_{samp})	175 ns
Length of CP (N_{cp})	64

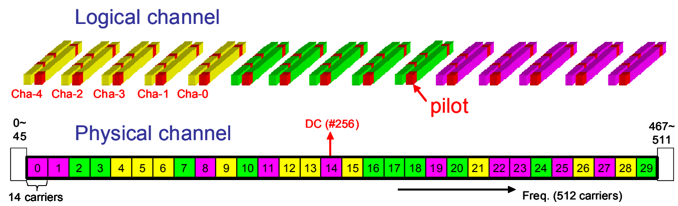

Figure 1. OFDMA air interface

Fig. 1 illustrates the structure of the OFDMA symbol cluster on the DL. Within an OFDMA symbol, a total of 30 physical clusters (or 15 sub-channels) are mapped (after renumbering and permutation of the logical clusters) as specified in [2]. Each sub-channel has 24 data carriers and 4 pilot carriers. The 15 sub-channels are assigned to three segments and allocated to three sectors within a cell. Hence up to 15 users can be supported. A frequency reuse factor of 1 is assumed between sectors to satisfy our reliability, coverage and capacity requirements.

The use of AMC allows the system to adjust the channel modulation and coding scheme in sympathy with the SNR of the link. For high SNR values, the system will select its highest throughput scheme (e.g., ¾ rate 64-QAM). As mentioned previously, MIMO techniques are also applied in the form of SM and STBC. The link throughput for each user is calculated from the Packet Error Rate (PER) as follows: $C_{throughput} = D \times (1 - PER)$, where $D = \frac{N_D N_b R_{FEC} R_{STC}}{Ts}$ represents the transmission date rate, and N_D, N_b, R_{FEC}, R_{STC} and T_s denote the number of assigned data subcarriers, bits per subcarrier, FEC coding rate, space-time coding rate and the OFDMA symbol duration of the user.

III. Application Environment and Conditions

The radio channel plays a key role in the evaluation of transceiver parameters such as link adaptation and multi-user scheduling. The scattering of signals together with time variations causes fading in both the time and frequency domains. In this section we analyse the channel characters using the WINNER model, which is built on the 3GPP2 Spatial Correlated MIMO (SCM) channel model. The SCM model is commonly used to characterise cellular environments [7]. Within the model, each resolvable path is characterized by its own set of spatial channel parameters (such as angle spread, angle of arrival and power azimuth spectrum). The 3GPP2 model defines three typical cellular environments, namely urban-micro (cell radius less than 500m), urban-macro, and sub-urban-macro (approximately 1.5km cell radius). These scenarios have mean RMS delay spreads of 0.25, 1.7 and 1.4µs respectively. Shadowing is applied to each link based on a 10dB and 8dB standard deviation for the NLoS urban microcell and macrocell channels respectively. The average pathloss models as a function of separation distance are given by

$$P_{loss\_micro} = 34.53 + 38\log_{10}(d) \quad dB \qquad (1)$$

$$P_{loss\_macro} = 34.53 + 35\log_{10}(d) \quad dB \qquad (2)$$

where d is the distance between the BS and a given MS. We assume that the BSs are placed at heights of 30 m with a transmit power of 40dBm (10 Watts) and an antenna gain of 15dBi. The MSs (with heights of 1.5m) are randomly deployed (with a uniform distribution) over the cell.

Assuming a fixed transmit power, Fig. 2 presents the PDF of the received power for the urban-micro and urban-macro cases considered in this paper. It can be seen that the received power within the urban macrocell (r = 1.5km) is much reduced compared to the microcell (r = 500m). This is due to the higher values of pathloss and shadowing at larger separation distances. The 802.16 standard defines the minimum received power for different modulation and coding modes (as a function of channel bandwidth) [1]. For example, for a 5 MHz bandwidth, minimum receiver input level sensitivities of -86 dBm and -71 dBm are specified for ½ rate QPSK and ¾ rate 64-QAM, respectively. For licensed spectrum, an Effective Isotropic Radiated Power (EIRP) of 55~57 dBm is acceptable for a macro BS. Given this limitation, QoS in a WiMAX network cannot be achieved by simply increasing the transmit power. Table 2 lists the SISO OFDMA-wireless MAN PHY requirement for the SNR [1]. For example, an SNR of 9.4 dB is required for the ½ rate QPSK mode. Fig. 3 shows that 15% of users in the urban microcell cannot achieve this value, and hence cannot support the ½ rate QPSK mode.

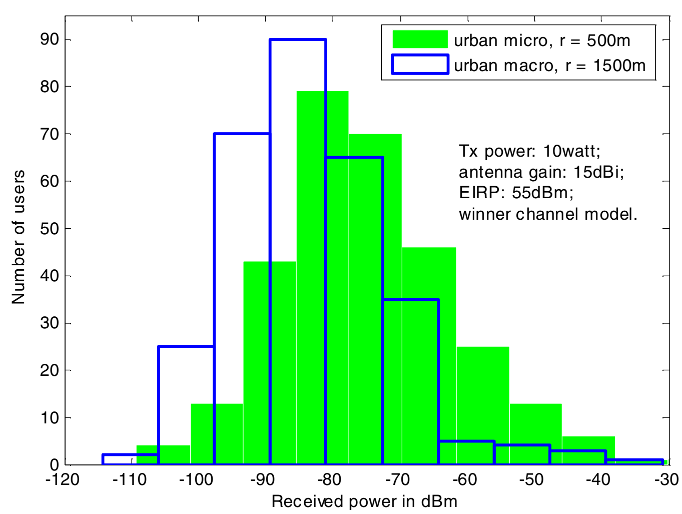

Figure 2. PDF of received power

TABLE 2
RECEIVER REQUIREMENT FOR OFDMA

Modulation	Eb/No	Coding rate	Receiver SNR
QPSK	10.5 dB	1/2	9.4 dB
		3/4	11.2 dB
16-QAM	14.5 dB	1/2	16.4 dB
		3/4	18.2 dB
64-QAM	19.0 dB	2/3	22.7 dB
		3/4	24.4 dB

Fig. 4 presents PHY layer simulation results for the case of 3 user OFDMA, where 5 sub-channels are assigned to each user. For ½ rate QPSK, the peak throughput of each user is given by $D = \frac{(5\times 24)\times 2\times 1}{100.8\mu s} \approx 2.4\,Mbps$. The overall system throughput in this case is 7.2 Mbps. Results show that the 15% outage probabilities agree with those calculated from Fig. 3. This occurs since the system cannot tolerate high PER (i.e. beyond a level of 10%).

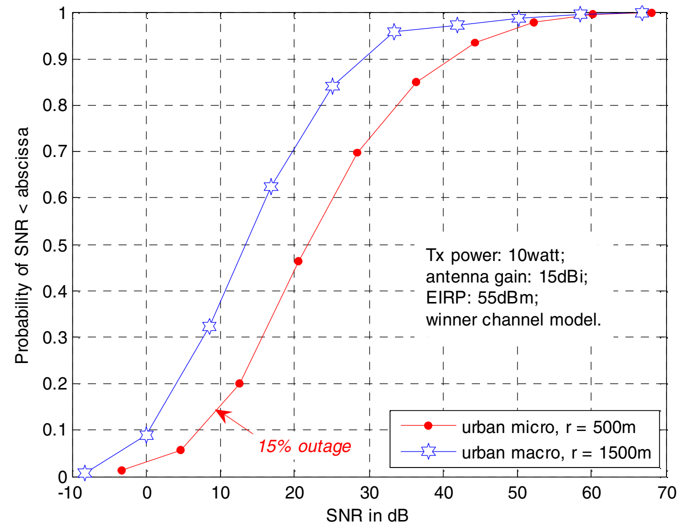

Figure 3. Probability of SNR

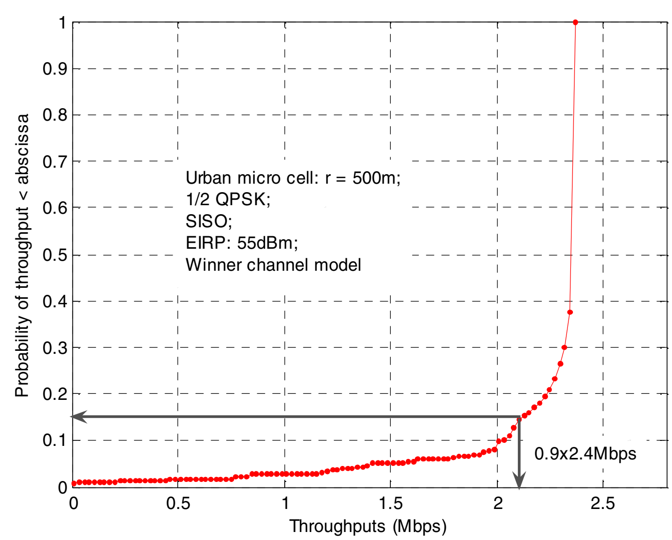

Figure 4. SISO sytem throughputs for micro cell (with ½ QPSK)

IV. CASE STUDY AND PERFORMANCE ANALYSIS

In this section we provide results for PER vs SNR, area coverage, system throughput and spectral efficiency. Once again, channel data was produced using the WINNER models [8]. We use a 3 sector BS to transmit on the DL to 3 users on each OFDMA symbol. We also assume ideal channel estimation with perfect link adaptation.

Fig. 5 illustrates the STBC and SM performance for a 2x2 MIMO-OFDMA system. Since STBC reduces the fade margin, higher modulation modes can be used. At an SNR of 32 dB, all modes can be used with STBC, however SM can only use the ½ rate QPSK scheme. Previous results from Fig. 3 indicate that approximately 73% and 92% of users have an SNR less than 32dB in urban-micro and urban-macro environments, respectively. A combination of MIMO, AMC and flexible sub-channelization is required to maximize performance.

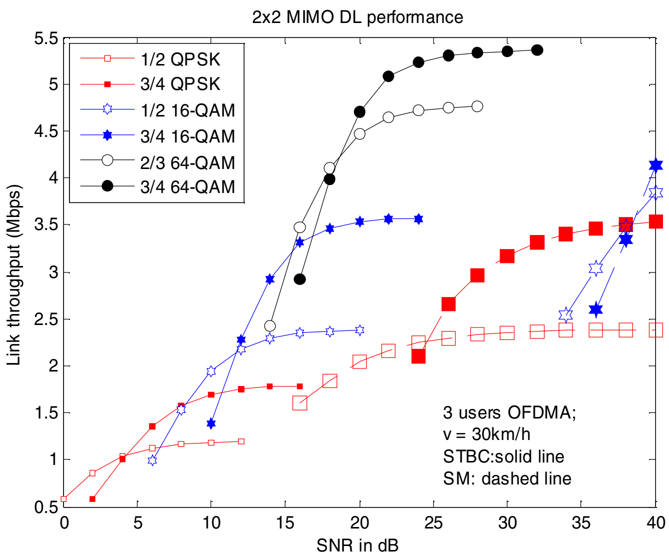

Figure 5. Comparision of STBC and SM for urban macro enveronment

To evaluate the area coverage and system throughput, the simulator deploys a total of 300 MSs. These are uniformly deployed within the urban macro cellular coverage area (cell radius of 1.5km), and the urban microcellular area (cell radius of 500m) as defined by 3GPP2. Each BS-MS link undergoes fast fading, with statistics based on 1000 channel snap-shots. Fair scheduling is assumed such that all users have an equal opportunity to access the BS (users are uniformly selected without any other constrains, e.g., SNR). For link adaptation, we choose the modulation and coding mode that maximizes the throughout while maintaining a PER < 10%.

Table 3 lists the coverage and system throughput for the micro and macrocell cases. For the 2x1 Multiple-Input Single-Output (MISO) STBC system, the antenna separation at the BS was set to 10 wavelengths in order to improve the transmit diversity gain. Results demonstrate that an approximate 3 Mbps throughput improvement can be achieved with the use of STBC transmit diversity in an urban microcell. This gain arises since more users (49%) are able to operate with the highest throughput mode (3/4 rate 64-QAM) compared to the SISO case (where only 29% of users support this mode). When 2x1 STBC is employed, the outage probability falls to 7% in the microcell. However, the large BS-MS separation distances in the macrocell degrades the level of WiMAX coverage and throughput compared to the previous microcell. Even with transmit diversity, the macrocell still experiences a 25% outage probability. In the macrocell throughput rates of just 5.4 Mbps and 6.3 Mbps are provided by the SISO and 2x1 STBC systems respectively. If the macrocell radius is reduced to 1km, the 2x1 STBC system achieves a throughput of 9.24 Mbps with an 8% outage probability (see Fig. 6 for details). These results demonstrate that the choice of cell radius has a significant impact on system performance, and also the impact of enhancements such as STBC transmit diversity.

TABLE 3
RECEIVER REQUIREMENT FOR OFDMA

	Urban micro		Urban macro	
	SISO	2x1	SISO	2x1
1/2 QPSK	23%	7%	21%	20%
3/4 QPSK	-	9%	13%	15%
1/2 16-QAM	16%	10%	11%	14%
3/4 16-QAM	11%	14%	8%	9%
2/3 64-QAM	6%	6%	4%	3%
3/4 64-QAM	29%	49%	10%	14%
Outage probability	15%	5%	33%	25%
System throughput (Mbps)	8.7	11.7	5.4	6.3

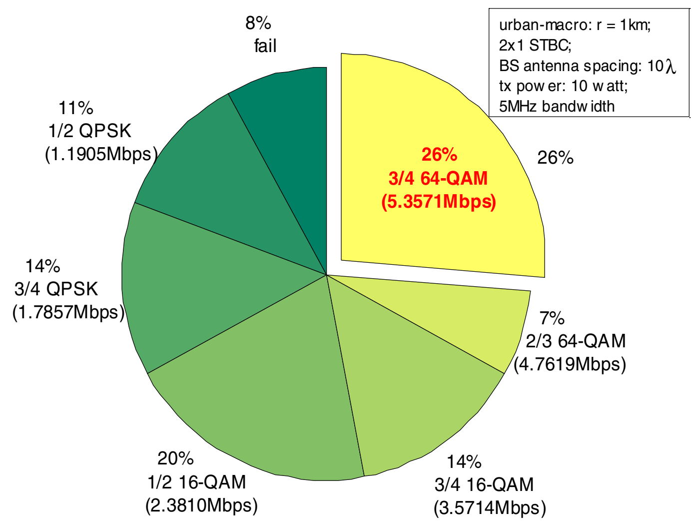

Figure 6. Performance for 1km cell radius (throughput = 9.24 Mbps)

Fig. 7 shows the WiMAX spectral efficiencies in terms of bps/Hz/km^2 over the cell area. The 2x1 STBC system provides a greater spectral efficiency than the SISO system, especially in the urban microcell, which shows a 32% improvement. As the cell radius is increased, the diversity gain is degraded. For example, only an 18% improvement is seen in the 1.5km radius macrocell.

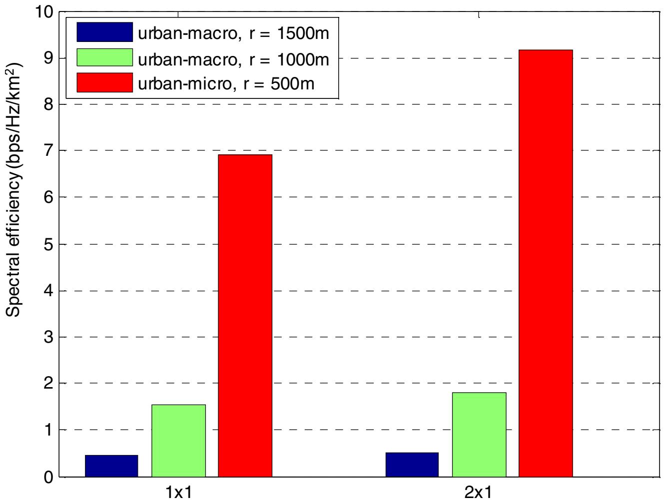

Figure 7. Comparations of spectrum efficiencies

With transmit diversity, satisfactory coverage can be achieved at the EIRP levels defined previously up until a cell radius of around 1km, as shown in Fig. 6. To realize coverage up to a cell radius of 1.5km in a macrocell, relay and MIMO techniques are required. It is well-known that relays can be deployed to enhance coverage and, in many cases, capacity. Relays are currently being considered within the 802.16j study group. The technology is being promoted to enhance performance in the broadband wireless market. A relay-based WiMAX system is proposed to improve the QoS (Quality of Service) of cellular transmissions. Relays can be applied in either a single-hop or multi-hop architecture. Relay systems are well-suited for areas with low throughput, or high outage probability.

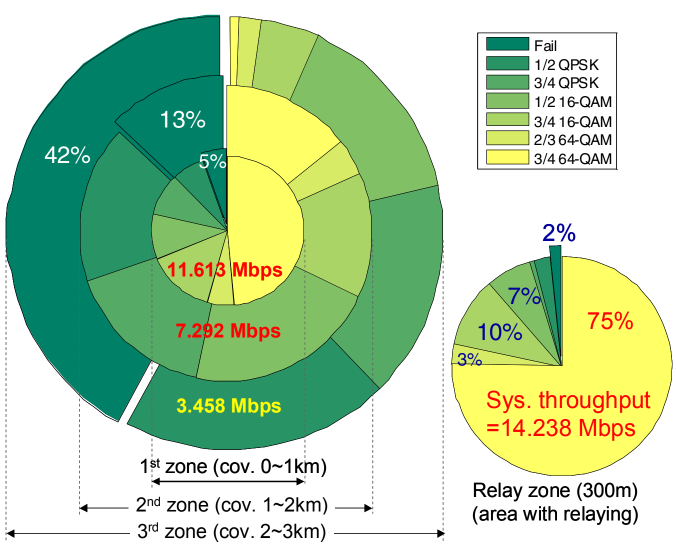

Figure 8. Performance of different zones for a full coverage

In order to study the use of relays, we define three areas for full coverage, as shown in Fig. 8. In the 3rd zone (diameter of 2~3km), the QoS cannot be guaranteed without the use of relays with this system profile (specifically, 42% of users fail without relays). In the relay zone (same antenna configuration as the BS with a single relay covering a radius of up to 300m), the transmit power of each relay station (RS) is only a half that of the BS, however the system can achieve a capacity of up to 14.2 Mbps (which represents a 305% improvement compared to the 3.5 Mbps value without relays). Using relays, the outage probability is reduced to 2%, as indicated in Fig. 8. It should be noted that the quoted results do not include the overheads of supporting the relaying process. Also for full coverage, different numbers of RS are employed in different zones (e.g., a maximum of 8 RSs for the 2nd zone). This kind of set-up is only used for our statistical study. For practical relay deployment, the RS should be applied to cover any coverage holes.

Our final study explores the impact of applying 2x2 MIMO in the form of STBC in the urban WiMAX system. In general, the system performance is improved compared to the earlier 2x1 STBC system, as summarised in Table 4. However, the MIMO system still experiences a 14% outage probability in the outer (3rd) zone without the use of relays. Hence, although MIMO improves performance, without relays we still fail to meet the system target of 90% coverage for the 1.5km radius macrocell. With relays enabled, the capacity is enhanced and the outage probability is reduced to less than 1%. In the MIMO case, the relay links also utilise 2x2 STBC with a 300m coverage radius to cover the 3rd zone. Results indicate that relay deployment is a powerful technique for meeting the coverage requirements of WiMAX in urban macrocells. The benefits of relaying are much larger in the 3rd zone, than the 2nd zone. Furthermore, with the potential advantage of relay deployment, the efficiency of relay deployment will be a critical issue for future studies on practical application, such as overhead, latency, etc.

TABLE 4
COMPARISON OF 2X1 AND 2X2 STBC WITH RELAY GAIN

		1st zone (r = 0.35~0.5km)		2nd zone (r = 0.5~1km)		3rd zone (r = 1~1.5km)	
		Cap.	**Cov.**	**Cap.**	**Cov.**	**Cap.**	**Cov.**
2x1 STBC	**Non-relay**	11.6	95%	7.3	87%	3.5	58%
	With relay	n/a	n/a	14.2	98%	14.2	98%
	Relay gain	n/a	n/a	95%	11%	305%	40%
2x2 STBC	**Non-relay**	14.1	98%	12.3	98%	8.1	86%
	With relay	n/a	n/a	15.6	~100%	15.6	~100%
	Relay gain	n/a	n/a	27%	2%	93%	14%

Cap.- Capacity (Mbps); **Cov.-** Coverage; No overhead and latency considered

V. CONCLUSIONS

The performance of mobile WiMAX systems is highly dependent on the operational environment, which influences the pathloss, shadowing and spatial correlation between antenna elements. Achieving high throughputs with low outage probability is a challenge, particularly in macrocells. This paper has presented a range of results based on environmental assumption taken from 3GPP2 and the IST-WINNER project. Results show that while SM increases the capacity of a single link, it requires high SNR levels (in many cases greater than

32dB). For an urban macrocell (radius of 1.5km), around 92% of users were seen to experience SNR levels below this threshold, and hence would struggle to exploit SM. STBC offers diversity gain and can be used to increase system coverage. When combined with AMC, the spectrum efficiency was seen to improve (in bps/Hz/km^2) relative to the SISO case by up to 32%. Furthermore, resulted showed that for low outage probabilities, 2x2 STBC should be considered. However, even 2x2 STBC failed to meet the outage probability in the urban macrocell (radius of 1.5km). Results clearly showed that even the combined exploitation of MIMO, OFDMA and AMC could not achieve satisfactory performance in the larger macrocells. To tackle this problem the use of radio relays was explored. Initial results showed that in combination with MIMO-STBC (2x1 and 2x2), relays could achieve near ideal coverage in a mobile WiMAX system.

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